NAUTICAL LABORATORY

CALIFORNIA INSTITUTE OF TECHNOLOGY

HYPERSONIC RESEARCH PROJECT

Memorandum No. 33

July 2, 1956

RESISTANCE THERMOMETER FOR HEAT TRANSFER MEASUREMENT IN A SHOCK TUBE

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ARMY ORDNANCE CONTRACT NO. DA-04-495-Ord-19

GUGGENHEIM AERONAUTICAL LABORATORY
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ABSTRACT

This report describes a method for the application of the well-known principle of the resistance thermometer to the problem of measuring surface temperatures and heat transfer rates under highly transient conditions, such as are experienced in a shock tube. By using a thin platinum film sputtered on glass, a resistance thermometer gage is obtained which has a response lag of less than 1 μ sec, a linear output of 2-3 mv/^{o}C, repeatability and durability. The gage preparation, including the sputtering technique, calibration method, and response characteristics are discussed, and some measurements of surface temperatures and heat transfer rates on models in the shock tube are presented in order to illustrate the performance that can be expected from this instrument.

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NOMENCLATURE

a_1	speed of sound ahead of the incident shock
A	area, sq. cm.
C_p	specific heat at constant pressure, $\frac{\text{cal}}{\text{gr, }^{o}\text{C}}$
ΔE	voltage rise, volts
h	enthalpy, cal/gr
I	current, amp.
k	thermal conductivity, $\frac{\text{cal}}{\text{cm, }^{o}\text{C, sec.}}$
M_s	shock wave Mach no., u_s/a_1
p	pressure, mm Hg
R	resistance, ohms
$\dot{q}$	heat transfer rate, cal./sec. cm^2
T	temperature, ^{o}C
t	time, sec.
V	voltage, volts
α	coefficient of resistivity, $1/^{o}C$
δ	thickness, cm.
$\varkappa$	thermal diffusivity = $(k/\rho C_p)$ $(cm^2/sec.)$
ρ	density, gr/cm^3
ω	frequency, 1/sec.

Subscripts

$( )_o$	initial conditions of film
$( )_f$	film
$( )_b$	backing material

I. INTRODUCTION

Current interest in high speed flight has stimulated the development of the shock tube as a device for simulating high stagnation temperatures in supersonic and hypersonic flow. The extremely short duration of uniform "hot" flow, of the order of 50 - 500 μ sec., dictates extremely fast response for any instrument applied to this problem. Recently several investigators have utilized thin metallic films as resistance thermometers to measure transient surface temperatures or heat transfer rates. A brief note[1] sketched some of the main features of a thin platinum film gage developed at GALCIT, which has a response time of less than 1 μ sec., linear output of about 2 - 3 mv/^{o}C, durability, repeatability, and a small resistance change over a large number of test runs. The present report describes this gage in some detail, including sputtering technique and construction, response characteristics and calibration, and associated electronic instrumentation. Some preliminary measurements of surface temperatures and heat transfer rates on models in the shock tube are presented in order to illustrate the performance that can be expected from this instrument.

II. THIN METALLIC FILMS AS TEMPERATURE SENSITIVE ELEMENTS

Thin metallic films with very low "thermal-inertia" have been employed both as thermocouples and as resistance thermometers. A film thermocouple developed at the Midwest Research Institute[2] is constructed by evaporating a thin nickel film ($\sim 10^{-6}$ cm. thick) on a steel housing, thus obtaining a Ni - Fe junction. This thermocouple

shows an extremely fast rise time ($\sim 1\,\mu$ sec.); however, the output is low ($\sim 18 \times 10^{-6}$ volts/^{o}F), and is also non-linear. This gage was used for the measurement of surface temperatures in gun barrels.

For shock tube research the resistance thermometer appears to be more promising, and such instruments have been developed by Emrich and Chabai[3, 4], W. Bleakney[5, 6], A. Kantrowitz, and by R. Vidal for the C. A. L. shock tube. The main differences between these elements lie in the method of applying the film. The methods usually employed are painting, evaporation, and sputtering. The simplest technique is to apply the film by using a special metallic paint, which may be silver or platinum paint. Special metallic pastes such as "Hanovia paste"* have also been used. The strip is then baked to evaporate the solvent, and a film of the desired metal is left on the model. This technique, although not requiring any complicated equipment, has the following disadvantages: (1) no control over the uniformity of film thickness; (2) no control over total amount of material in film. Consequently there is no control over the film resistance.

The evaporation technique was used successfully by Chabai and Emrich and also by Bleakney at Princeton University. A thin gold film is evaporated over a thin plastic tape which is later attached to the model. Leads are connected by silver painting, and film resistance is controlled by cutting a suitable size out of the "golden" plastic tape.

The sputtering technique used at GALCIT[1] provides a controllable method for applying a thin metallic film on an electrically insulating

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* Trade name for platinum paste, manufactured by Hanovia Corp.

material. Film resistance (and thickness) is controlled by the sputtering time. The sputtered element is easy to handle and leads can be soft-soldered directly to the element. This element is rugged enough to stand the punishment in the shock tube, and the film is adherent so that erosion is not excessive, at least up to shock Mach numbers of 7-8.

Comparison of these techniques leads us to believe that the sputtering technique provides the most controllable method for applying a thin film and may also prove to be the mose rugged compared to the evaporation and painting techniques. However, the sputtering technique is still an art and requires a considerable amount of trial and error before satisfactory results are obtained. For this reason the sputtering procedure which has been successfully used at GALCIT will be described in some detail in the next section.

III. SPUTTERING TECHNIQUE

The sputtering phenomenon at the cathode of a glow discharge was discovered in 1852 by W. R. Grove. However, the exact mechanism of the process is still not fully understood (Strong, Ref. 7). One theory holds that the emission of metal molecules is caused by thermal evaporation at the high temperature of the cathode. The second theory implies that there is an excitation of metal molecules by gas ion bombardment, in a manner similar to the emission of electrons by photon excitations. In spite of this uncertainty about the exact mechanism, the type of apparatus required for successful sputtering of metal films over glass or similar material is well known, but the exact geometry of the apparatus and sputtering procedure must be determined empirically.

A typical set-up for the sputtering process is shown in Fig. 1. A standard bell jar 5" O. D. and 12" high is used. In its top a hole is drilled for the cathode connection. The bell jar stands on a ground steel base, and a vacuum seal is provided by a layer of high vacuum grease. An aluminum table of adjustable height is attached to the steel base to serve as an anode and base for the elements to be sputtered. The element and the cathode are enclosed by a 3" O. D. glass cylinder which prevents sputtered metal from spreading all over the bell jar. Glass or quartz tubes are used to cover bare parts of the cathode (except the sputtered metal) in order to prevent arcing.

The importance of eliminating contaminating materials from the system cannot be over-emphasized. A small rubber or plastic gasket that may out-gas when heated, or impurities on the element, or any carbon-compounds, etc. which are introduced into the system, will cause many frustrating hours of unsuccessful trials. The glass should be cleaned in acetone or a similar solvent.

The important parameters for sputtering are: (1) sputtering metal, (2) gas envirommment, (3) vacuum level and gas circulation, (4) current and voltage applied, and (5) distance between cathode and model. A list of possible sputtering metals is given by Strong[7] for different gas envirommments. The authors have obtained successful films with platinum, silver, and copper; however, other metals can be sputtered as well. The gas in the apparatus can be air, argon, N_2, H_2, or 0_2. For simplicity air was used exclusively, although faster results could be obtained by using an argon atmosphere. The conditions found to be best with the GALCIT apparatus for the sputtering

of platinum are the following: (1) cathode: platinum bar 0.065" x 1/4" x 2"; (2) distance between cathode and element varies between $1\frac{1}{2}$" - 2" and best results are obtained at about 1-3/4"; (3) voltage is 800-1100 volts and current is 50-60 ma; (4) the pressure is 2 to 3 mm Hg. abs. and an air leak corresponding to a pressure rise of about 0.1 mm Hg/minute is maintained. The leak is balanced by the vacuum pump during the sputtering process.

The platinum glows with a reddish-blue halo, and a glow also appears around the sputtered element. A dark zone of about 3/4" is maintained between the two glowing parts.

IV. CONSTRUCTION OF HEAT TRANSFER GAGE

The best electrical insulators utilized as backing material for the thin metallic films are glass and quartz. The shape of the glass or quartz element can be ground to fit the test model, or for simple geometrical models the model itself can be made out of glass, e.g., glass spheres and cylinders, etc. A heat transfer gage to be inserted in a test model is prepared as follows: First the insert backing element is cut and lapped to the required dimensions. Then two opposite unexposed edges are sputtered for about $\frac{1}{2}$ to 1 hour. These edges are used later for soldering the electrical leads. The element is then baked for $\frac{1}{2}$ hour at 1100°F in an oven and is allowed to cool slowly. Now the sensitive film is sputtered on the test surface. The sputtering time is adjusted to obtain a film resistance of about 40-60 ohms. For films $\frac{1}{2}$" to 1" long and .05" wide the sputtering time is in the order of 1 - 3 hours. After the test film is sputtered the element is baked again at 1100°F for about $\frac{1}{2}$ hour and again left to cool slowly. Electrical leads can then be soft-soldered to the sputtered unexposed edges, using

regular soft-solder flux. The gage is flush mounted in a groove in the model. A strip of blotting paper is inserted behind the element to absorb the shock and reduce the danger of breakage of the glass. Gages at several stages of assembly are illustrated in Figs. 2 and 3.

When the film is sputtered directly on the aerodynamic model, the leads can be soft-soldered to the test film after it is baked.

V. RESPONSE CHARACTERISTICS OF A SURFACE RESISTANCE THERMOMETER

The time required for heat to diffuse from the outer surface of the film to the interface between the metallic film and the backing material provides a measure of the response time of the film itself. Roughly, this diffusion time, t_d, is given by

$$t_d \sim \frac{\rho_f \; C_{p_f} \; \delta^2}{k_f} \tag{1}$$

where δ is the film thickness, and the subscript "f" denotes the properties of the film material. For platinum $(\rho_f \; C_{p_f})/k_f = 4.04$ in c.g.s. units, and if $\delta \sim 10^{-6}$ cm, or 100 Å, then $t_d \sim 4 \times 10^{-12}$ sec. Thus under almost all transient conditions the temperature of such a thin film is uniform across its thickness and is equal to the instantaneous surface temperature of the backing material itself.

So far as the backing material is concerned, the metallic film acts as a thermal capacitance of extremely small "thermal inertia". The surface temperature of the backing material approaches within a few per cent of the ideal response for zero film thickness in a "lag time"

t_ℓ of the order of (Ref. 8):

$$100 \times \frac{(C_{p_f} \rho_f)^2}{K_b \rho_b C_{p_b}} \delta^2$$

(Here "b" refers to the backing material.) If the backing material is quartz, and a platinum film of 10^{-6} cm thickness is used, then $t_\ell \sim 6 \times 10^{-9}$ sec. For a glass backing element $t_\ell \sim 6 \times 10^{-8}$ sec. The experimental evidence shows that the response time of these metallic films plus backing material is not longer and may be even faster than the rise time of some of the best available oscilloscopes, such as the Tektronix 535 with a rise time of $.03 \times 10^{-6}$ sec. and the DuMond 336 with a rise time of $.02 \times 10^{-6}$ (Fig. 4).

When the gage is utilized as a resistance thermometer the temperature rise of the film appears as a voltage variation. If this temperature rise is not too large, the relation between film temperature and electrical resistance is linear and can be written as

$$R_f = R_o \left[1 + \alpha (T_f - T_o)\right] \qquad (2)$$

where α is the coefficient of resistivity, the subscript "o" refers to initial conditions, and "f" refers to the instantaneous film conditions. With a constant current flowing through the film,* the instantaneous

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* Note that the heating due to the constant current I_o is negligible compared to the heat rates which are experienced in the shock tube. e.g., $I_o^2 R_o \sim 0.02$ watts/cm^2 while the heat transfer rates vary between 2-1000 watts/cm^2.

voltage rise is $\Delta E = I_o (R_f - R_o)$ so that

$$T_f - T_o = \frac{\Delta E}{I_o R_o a} \tag{3}$$

For a typical platinum film gage, $R_o = 50$ ohms, $I_o = 20 \times 10^{-3}$ amps, and $a = 0.002$ to $0.003/^{\circ}C$, so that an output of 2-3 mv per degree centigrade is recorded. By using the present recording equipment, which consists of a Tektronix 535 oscilloscope and Tektronix 121 wide-band preamplifier, with a combined resolving sensitivity of 0.5 millivolts, temperature variations of about $.5^{\circ}C$ can be resolved.

For a testing time up to 1000 μ sec. the heat pulse penetrates only a very shallow layer near the surface of the glass or quartz backing material. The depth of this layer is given roughly by

$$\delta_b \sim 3\sqrt{\frac{k_b\, t}{\rho_b\, C_{p_b}}}$$

For $t = 1000\,\mu$ sec, $\delta_b \sim 0.004$ cm. for glass, and $\delta_b \sim 0.010$ cm for quartz. Since the backing element is usually at least 0.5 cm. thick, and the length scale of temperature variations along the surface of a model is at least 10 times larger than δ_b, the backing material acts practically like a semi-infinite, one-dimensional solid heat sink. Thus the required relation between the surface heat transfer rate and the known film temperature change is obtained by solving the classical, one-dimensional heat conduction equation

$$\frac{\partial T}{\partial t} = \varkappa \frac{\partial^2 T}{\partial x^2} \tag{4}$$

for the region $x \geqslant 0$, subject to the boundary conditions

$$T(x, 0) = \dot{q}(x, 0) = 0, \qquad T(0, t) = f(t), \quad \text{and}$$

$$T(x, t) \longrightarrow 0, \quad \dot{q}(x, t) \longrightarrow 0 \quad \text{as} \quad x \longrightarrow \infty$$

Here $T = T_f - T_o$ and $\varkappa = k_b/(\rho_b C_{p_b})$. For the special case of a unit step-function in surface temperature, i.e., $T(0, t) = 0$ for $t \leq 0$ and $T(0, t) = 1$ for $t > 0$, we know that

$$\dot{q}(0, t) = \frac{k}{\sqrt{\pi \varkappa t}} = \sqrt{\frac{(k \rho C_p)_b}{\pi}} \; \frac{1}{\sqrt{t}} \tag{6}$$

(see for example Ref. 8). Therefore the surface heat transfer rate for an arbitrary surface temperature time history $T(0, \tau)$ is given by the relation

$$\dot{q}(0, t) = \sqrt{\frac{(k \rho C_p)_b}{\pi}} \int_0^t \frac{1}{\sqrt{t - \tau}} \; \frac{df}{d\tau} \; d\tau \tag{7}$$

where $f(\tau) = T(0, \tau)$, or by

$$\dot{q}(0, t) = \sqrt{\frac{(k \rho C_p)_b}{\pi}} \int_0^{\pi/2} g_1(\theta) \, d\theta \tag{8}$$

where $\theta = \sin^{-1} \sqrt{\tau/t}$ and $g_1(\tau) = 2\sqrt{\tau} \; \frac{df_1}{d\tau} = \frac{df}{d\sqrt{\tau}}$

The inverse relation connecting the surface temperature and the applied heat transfer rate is also useful. According to Carslaw and Jaeger (Ref. 9, p. 59, eq. 9)

$$T(0, t) = \frac{1}{\sqrt{\pi (\rho C_p k)_b}} \int_0^t \frac{\dot{q}(0, \tau)}{\sqrt{t - \tau}} \; d\tau \tag{9}$$

In addition to the special case $\dot{q} \sim 1/\sqrt{t}$, $T(0, t) = 1$ considered above, two other simple heat transfer rate input functions are of practical interest.

A. Step Function Heat Transfer Rate

In this case $\dot{q}(0, t) = 0$ for $t \leq 0$ and $\dot{q}(0, t) = \dot{q}_o$ for $t > 0$. According to Eq. 9

$$T(0, t) = \frac{2q}{\sqrt{\pi (\rho C_p k)_b}} \sqrt{t} \qquad (10)$$

B. Periodic Heat Transfer Rate

Iere $\dot{q}(0, t) = q_o \sin (wt + \epsilon)$, and the steady, periodic part of the response is

$$T(0, t) = \frac{q_o}{\sqrt{(k \rho C_p)_b}} \sqrt{\frac{1}{\omega}} \sin (\omega t + \epsilon - \frac{\pi}{4}) \qquad (11)$$

VI. METHODS OF CALIBRATION

According to the relations obtained in section 5 for the response characteristics of a film resistance thermometer, two physical parameters must be determined with precision: these physical characteristics are (1) a, the coefficient of resistivity; (2) the quantity $\frac{1}{\sqrt{(\rho C_p k)_b}}$

A. Determination of a

In the shock tube, film temperature changes of about 100°C have to be considered, so that the determination of the resistance change between the ice point (0°C) and the water boiling point (100°C) is sufficient. This measurement is similar to the determination of a for a hot wire anemometer, and is a standard procedure in this field.

B. Determination of $\frac{1}{\sqrt{(k \rho C_p)_b}}$

Because of the interpenetration of metal and glass that occurs at the interface between the thin film and the backing material, and the very shallow layer affected by the heat pulse, the physical quantities k, ρ, and C_p are not equal to the properties of the bulk material. Thus it is impossible to determine the above quantity by the standard steady-state methods with any degree of precision, and one is forced to use a transient technique. The simplest solution is to use a known heat input, measure the gage output, and thereby determine the parameter

$$\frac{1}{\sqrt{\rho C_p k}}$$

A constant heat rate input was chosen, and this input was obtained by the discharge of a large capacitor into the film. The capacitor was selected so that the time constant of its discharge would be much larger than the required test time. The calibration circuit is shown in Fig. 5 and the discharge characteristics of such a circuit are shown in Fig. 6. The first two pictures of Fig. 6 show the discharge of the capacitor through a regular stable resistance. For the first 200 μ sec. the discharge is very well described by a step function. Note that in the traces using fast sweeps all initial transients decay in about 1 μ sec. or less. The second part of Fig. 6 shows the output of the gage when the capacitor is discharged through the film. For the first 200 μ sec. the output is very well described by a parabolic variation with time (Fig. 7), which is predicted by the solution of the heat conduction equation for constant heat rate input.

The quantity $\frac{1}{\sqrt{\rho C_p k}}$ is determined from Eq. 10 by the following method:

The heat input $\dot{q}_o$ in cal/sec. cm^2 is given by

$$\dot{q}_o = \frac{I_o^2 R_o}{4.19 A} \tag{12}$$

where I_o = current flow in film in amperes; A = film area in cm^2; R_o = initial film resistance in ohms. The voltage output ΔE due to the heating of the film by the discharge is related to its resistance change ΔR by *

$$\Delta R = \frac{\Delta E}{V} \frac{(R_o + R_2)^2}{R_2} \tag{13}$$

where R_2 is the second resistance in the calibration bridge and

$$I_o = \frac{V}{R_o + R_2} \tag{14}$$

Now $T_f - T_o \equiv \Delta T = \Delta R/\alpha R$, and, by equation 10

$$\frac{\alpha}{\sqrt{\rho C_p k}} = \frac{4.19 \sqrt{\pi} \cdot A \cdot \Delta R}{2 \cdot R_o^2 \cdot I_o^2 \cdot \sqrt{t}} \tag{15}$$

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* Note that the relation between ΔR and ΔE in the calibration bridge (eq. 13) is different from the usual linear relation $\Delta E = I_o \Delta R$ which is used when the gage is operated at constant current for the heat transfer measurements (eq. 3). The current I_o in the calibration bridge is used both for heating of the film and for detection of resistance changes. Since the changes in I_o are of the same order as that of R_o, the more complicated equation 13 is obtained.

When only the heat transfer rate is of interest, the separate determination of α is not required since this method actually determines the quantity $\alpha / \sqrt{\rho C_p k}$ appearing in the relation between $T(0, t)$ and $\dot{q}(0, t)$

The resistances R_o, R_2 can be measured within $\frac{1}{2}$ per cent; the initial charging voltage V can be measured within 1 per cent; and the film output ΔE is obtained from oscilloscope records similar to those shown in Fig. 6, taken with a polaroid camera. Hence $\alpha / \sqrt{\rho C_p k}$ can be determined to about 4 - 5 per cent accuracy.

The values of α for the platinum films were found to vary between 0.0019 - 0.0022 $1/^oC$. The value of $\alpha / \sqrt{\rho C_p k}$ for these films with glass as a backing material varied between 0.05 - 0.09 using c. g. s. units. The value of α is considerably different from the bulk value which is 0.0038 $1/^oC$. The handbook value of $\alpha / \sqrt{(\rho C_p k)_{glass}}$ is .1315 for $\alpha = .0038$ $1/^oC$ and decreases to .0692 for $\alpha = .002$ $1/^oC$ which is in the range of the experimentally determined values.

VII. OPERATING CONDITIONS

In shock tube research the film resistance thermometer can be used either as a heat transfer rate gage or as a shock wave detection device for shock velocity measurements, or other timing operations.

When used as a heat transfer gage the film is operated within a circuit similar to one used for constant current operation of a hot wire anemometer, which is illustrated in Fig. 8. The accuracy of the heat transfer rate data is affected by the accuracy of measurement of the

film resistance* and the current flowing through it, (equations 3 and 9). These quantities can be easily measured to an accuracy of ½ per cent. Thus, with the 5 per cent accuracy in the calibration constant.the heat transfer rate can be measured with an accuracy of about 5 - 6 per cent.

When the film is employed as a gage for shock velocity measurement the arrangement illustrated in Fig. 9 is used. Current flows through the film and the output is fed through a pulse amplifier to a counter. This pulse can also be used for triggering associated equipment such as oscilloscopes, time delays, schlieren systems, etc.

VIII. PRELIMINARY RESULTS IN SHOCK TUBES

Preliminary tests were made with the gage at the "stagnation line" of a cylinder and on the shock tube wall. These models are shown in Fig. 3.

The heat transfer at the stagnation point of a blunt body is proportional to the difference between the stagnation enthalpy, h_s, and the enthalpy corresponding to the wall temperature, h_w. At very high gas temperatures $h_s >> h_w$, and so the heat transfer rate in the time available in the shock tube is very nearly constant[10]. For this heat rate input the surface temperature should increase as $\sqrt{t}$. Verification

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* This analysis assumes that there is no permanent resistance change due to erosion or pitting of the film. However, small resistance changes which may vary between 0 to 1 ohm (for 40-60 ohms gages) are observed at normal shock tube operation using properly scribed copper diaphragms. This change is believed to be due primarily to pitting by dust or dirt particles in the air and judging by experimental evidence occurs primarily after the arrival of the contact region.

of this parabolic temperature-time relation is shown in Fig. 10, and results of several runs are shown in Fig. 11.

On the shock tube wall the laminar boundary layer grows like $\sqrt{t}$ and the heat rate decreases like $1/\sqrt{t}$ (Ref. 8). For this heat input the solution is $T(0, t) = \text{const.}$, i. e., a step function in surface temperature. Fig. 12 shows the output of the wall gage. Although some deviations are apparent the general shape is in agreement with the predicted sudden temperature jump.

IX. CONCLUSIONS

This report describes a method for the application of the well-known principle of the resistance thermometer to a highly transient temperature variation by utilizing a thin metallic film. Quantitative heat transfer measurements can be obtained with the aid of the calibration method which is described here. Preliminary measurements of heat transfer rates in the shock tube at GALCIT indicate that this gage can be very useful in many applications where fast response is required, such as in ballistic ranges, flight test of missiles, rocket engines, etc. Application of this gage to quasi-stationary processes also appears to be a promising possibility.

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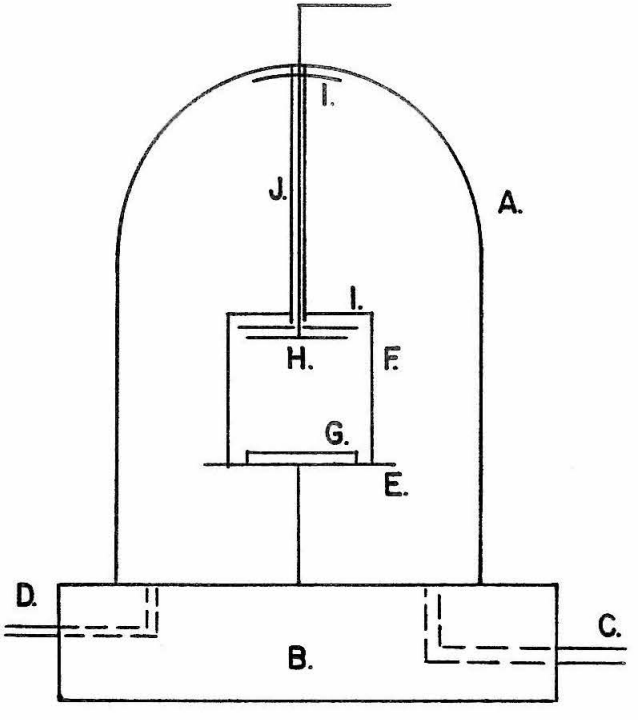


A. BELL JAR
B. STEEL BASE
C. VACUUM LINE, TO PUMP
D. CONTROLLED AIR LEAK
E. ALUMINUM BASE
F. GLASS TUBE
G. GAGE TO BE SPUTTERED
H. PLATINUM CATHODE
I. MICA INSULATION
J. PYREX TUBE

APPARATUS FOR SPUTTERING TRANSIENT TEMPERATURE GAGES

FIG. 1

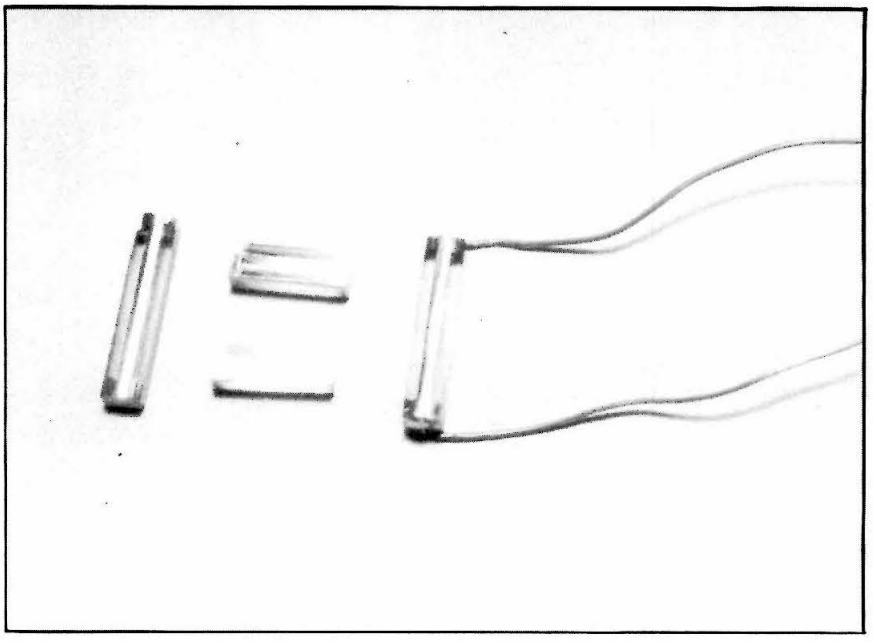


FIG. 2

RESISTANCE THERMOMETER GAGES

AT VARIOUS STAGES OF PREPARATION

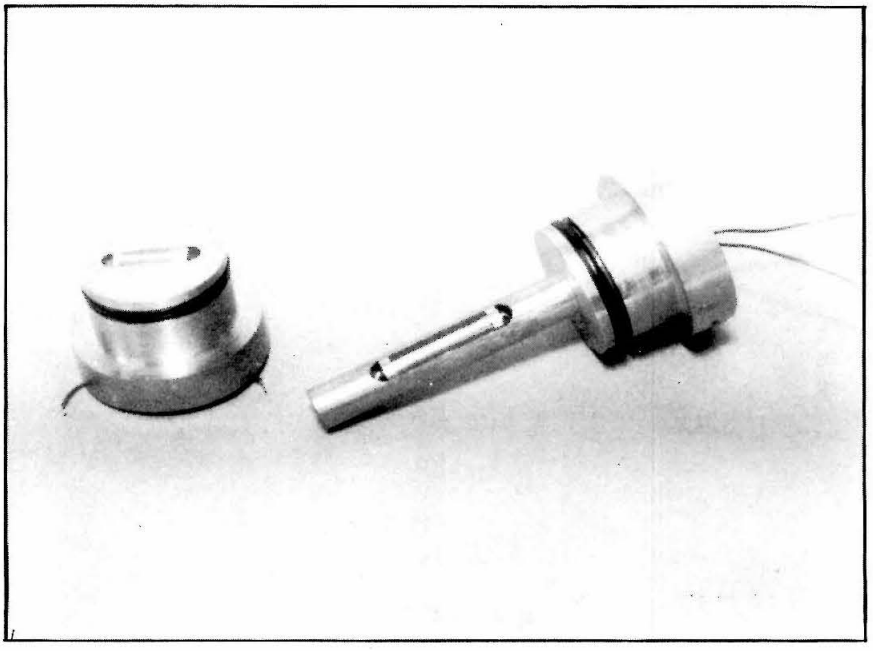


FIG. 3

GAGES INSTALLED IN MODEL

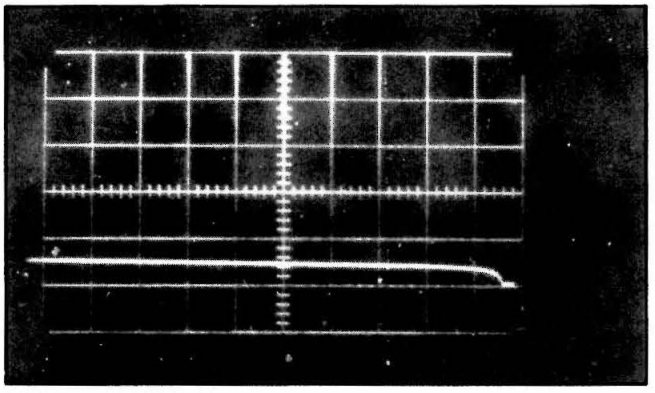
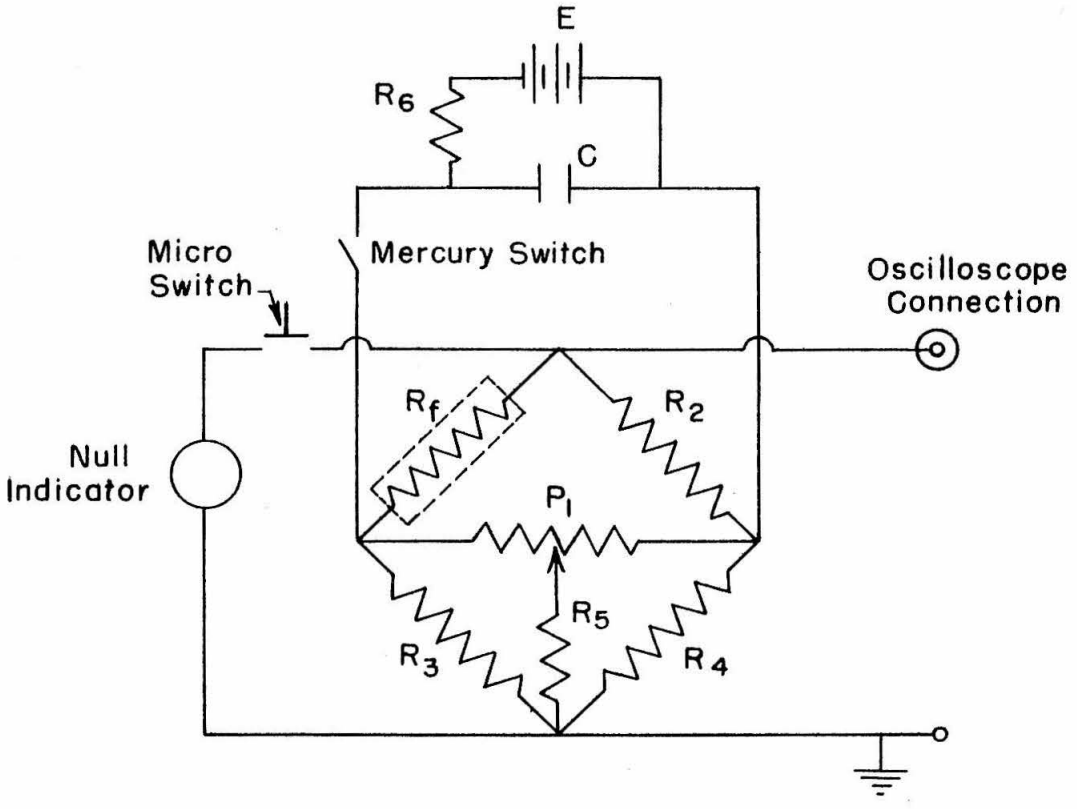


FIG. 4

RESPONSE OF GAGE AT "STAGNATION LINE" OF A CYLINDER

$M_s = 6.44$; $p_1 = 2.4$ mm Hg;

Sweep = 1 μ sec./div.; Sensitivity = .05 V/div.



R_f = Calibrated Film

$R_2 = R_3 = R_4 = 57$ Ohm

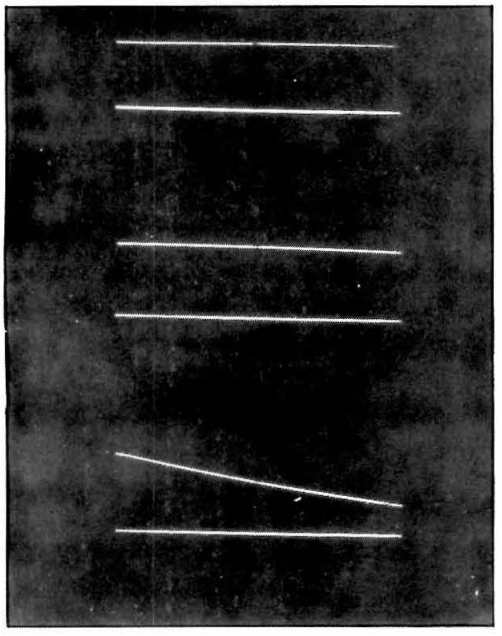
$R_5 = 270$ Ohm

$R_6 = 1000$ Ohm

$P_1 = 1000$ Ohm Pot.

$C = 600\ \mu F$

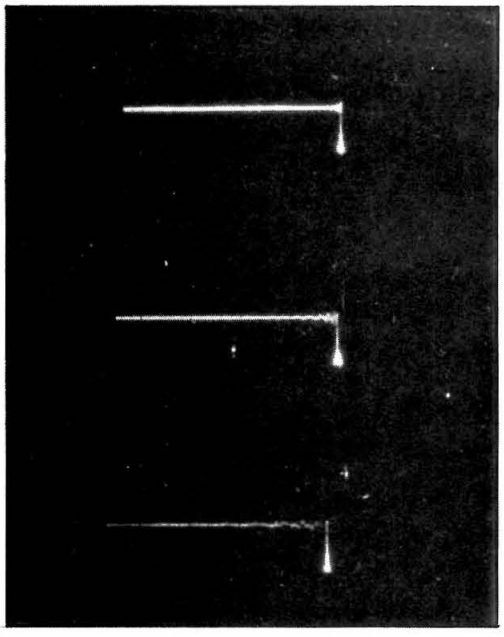
FIG. 5 CALIBRATION CIRCUIT



200 μsec

2 msec

20 msec

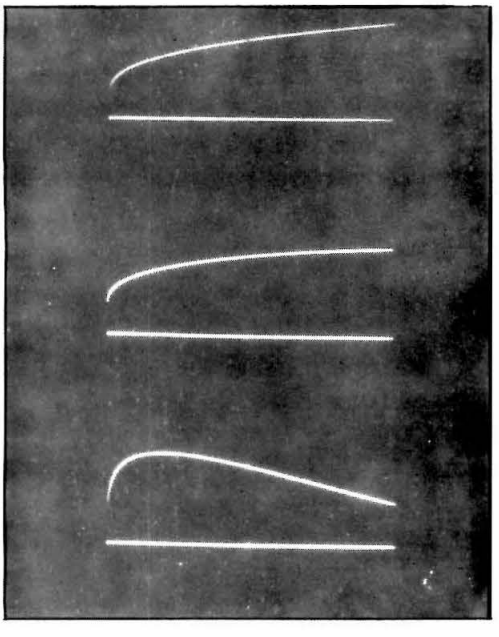


20 μsec

10 μsec

4 μsec

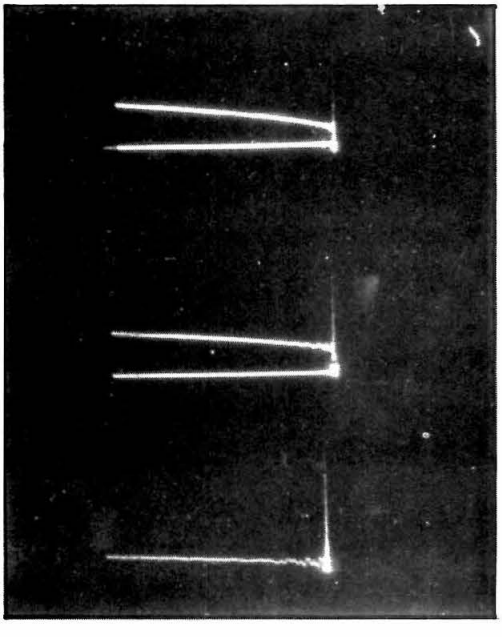
(a) Stable Resistance



200 μsec

2 msec

20 msec



20 μsec

10 μsec

4 μsec

(b) Resistance Gage

Characteristics of Calibration Circuit

FIG. 6

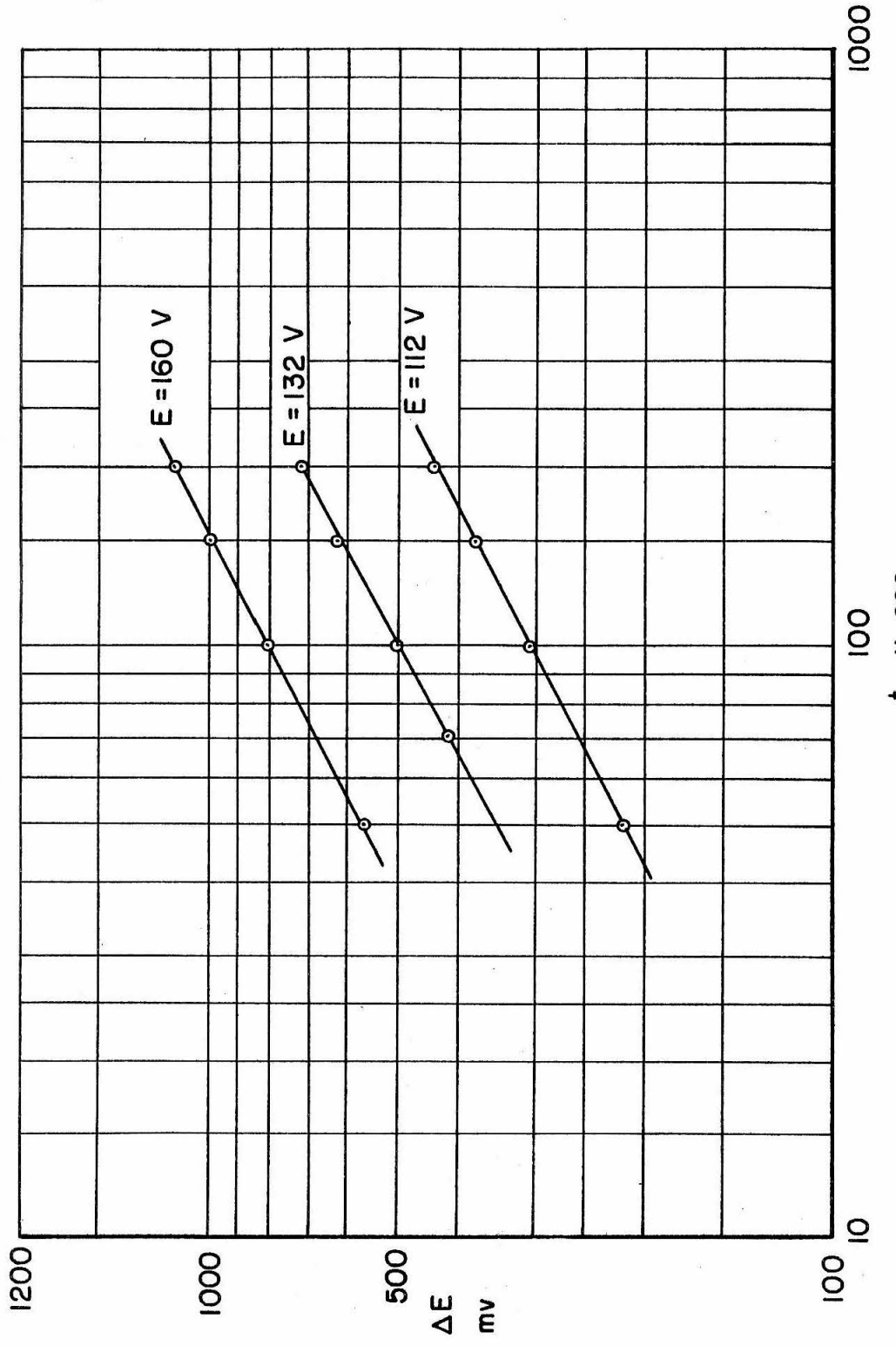


FIG. 7 GAGE CALIBRATION — $\Delta E \sim t^{0.50}$

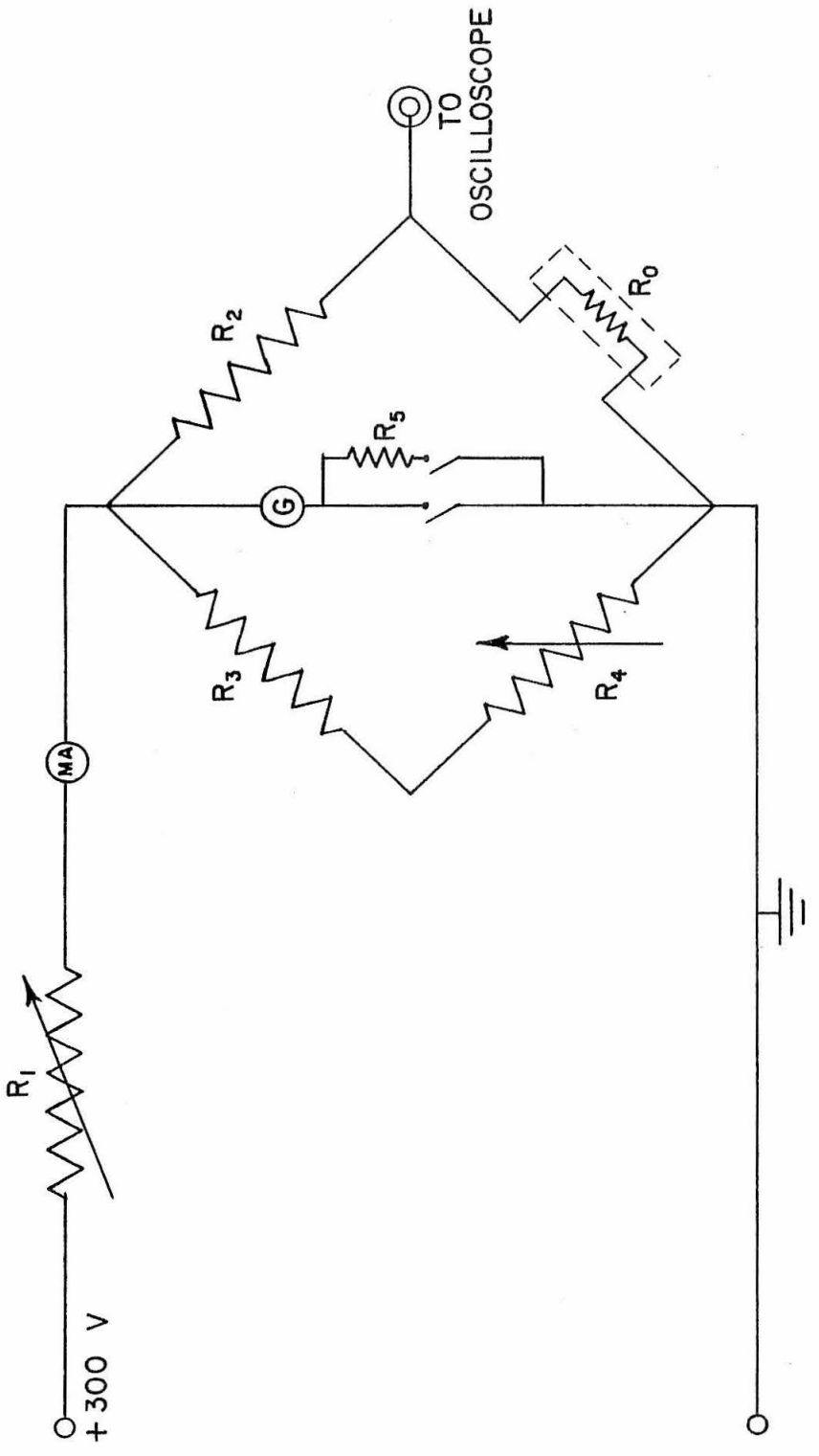


FIG. 8 BRIDGE CIRCUIT FOR RESISTANCE THERMOMETER OPERATION

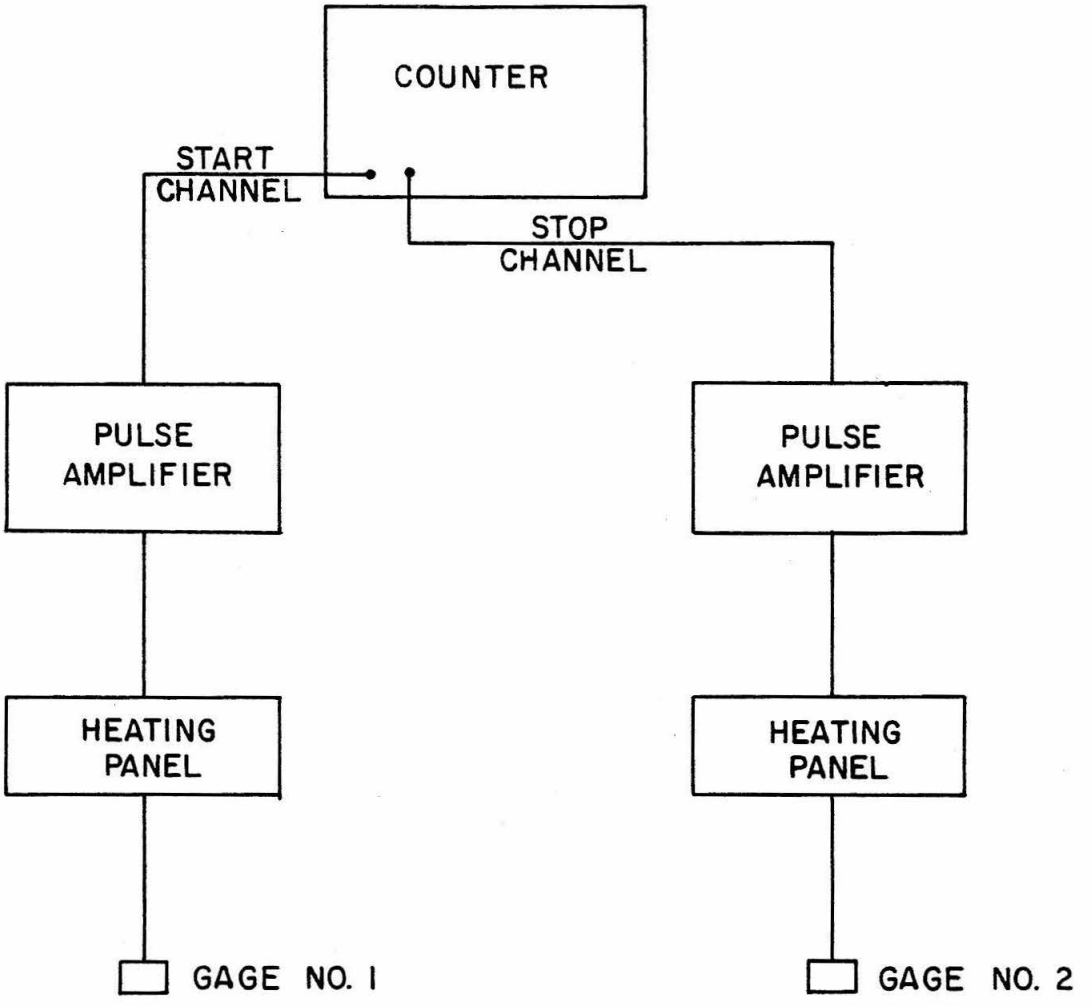


FIG. 9 BLOCK DIAGRAM FOR USE OF GAGE FOR SHOCK SPEED MEASUREMENTS

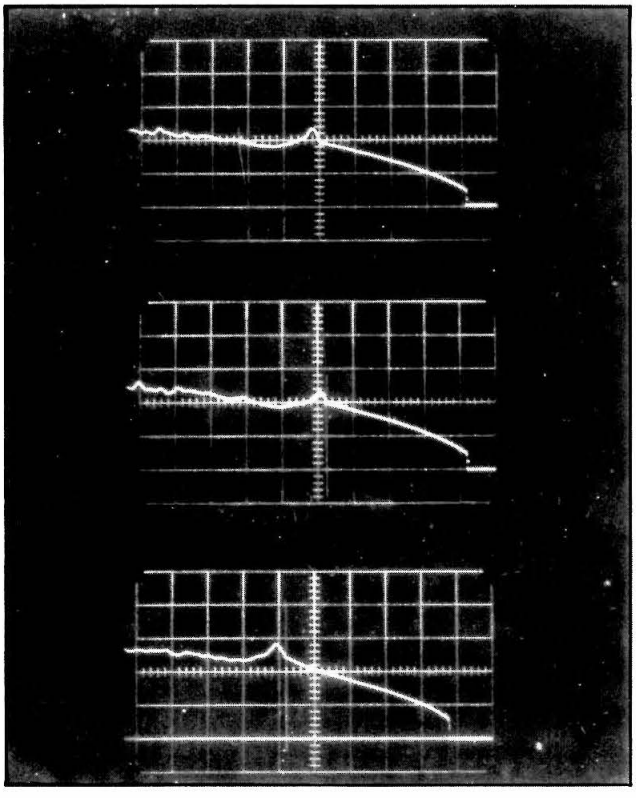


FIG. 10

GAGE RESPONSE AT THE STAGNATION POINT OF A CYLINDER

Sweep = 50 μ sec./div.; Sensitivity = .05 V/div.

Top:	M_s = 7.10	P_1 = 2.5 mm Hg	R_o = 48.9 Ω	I_o = 20 ma
Center:	M_s = 7.03	P_1 = 2.6 mm Hg	R_o = 51.5 Ω	I_o = 20 ma
Bottom:	M_s = 6.53	P_1 = 5.7 mm Hg	R_o = 52.3 Ω	I_o = 20 ma

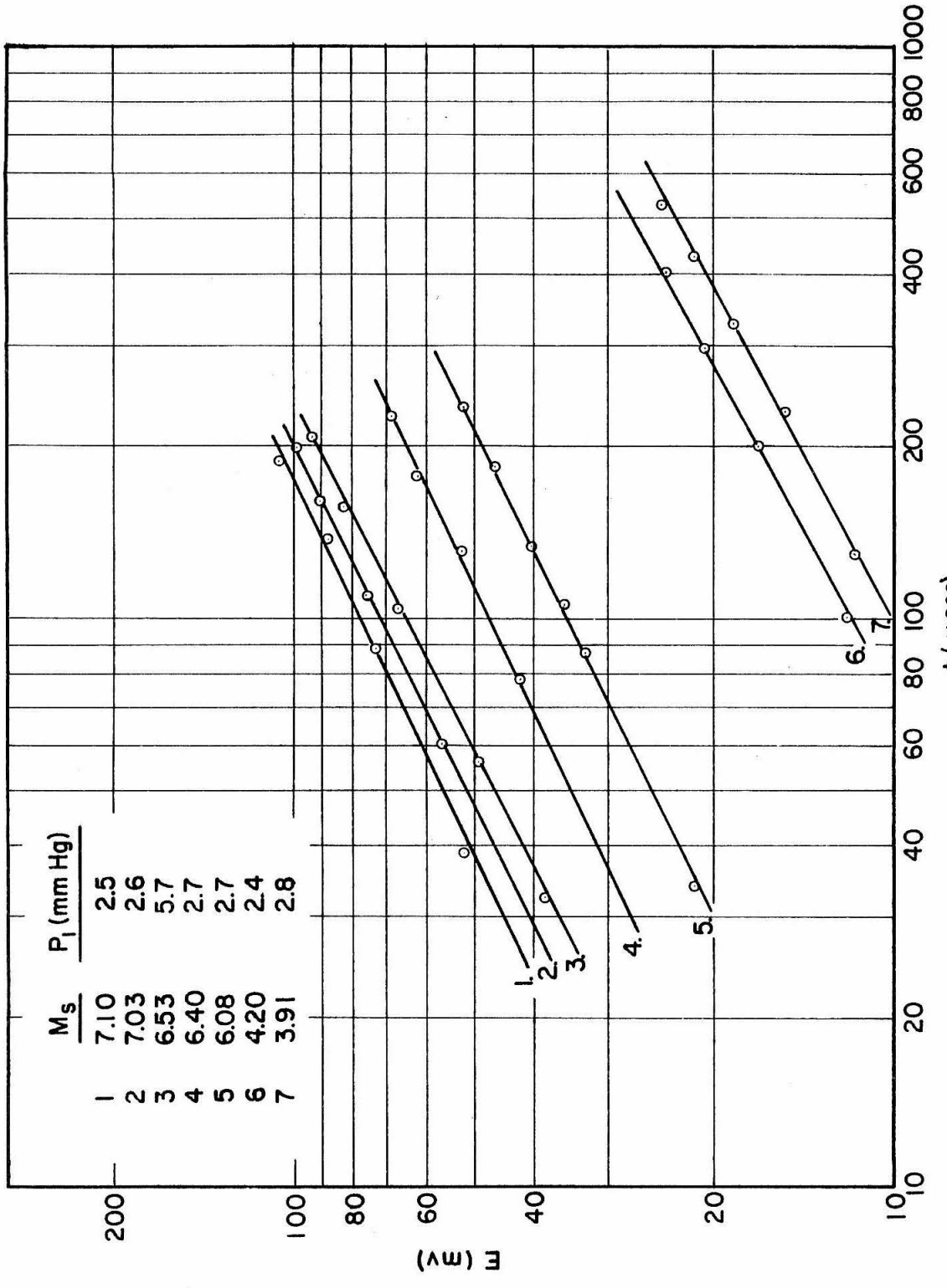


FIG. 11 GAGE OUTPUT AT THE STAGNATION POINT OF A CYLINDER

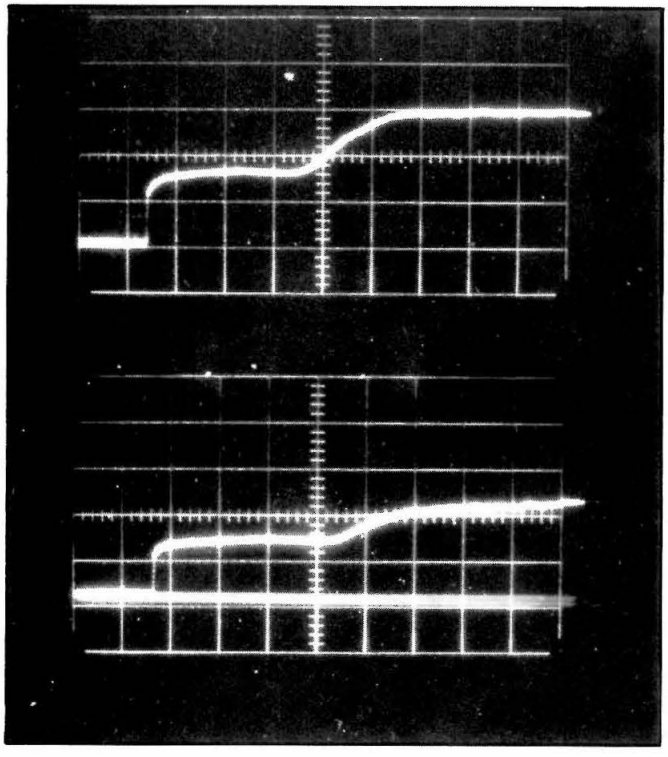


FIG. 12

GAGE RESPONSE ON THE SHOCK TUBE WALL

Sweep = 50μ sec./div.; Sensitivity = .005 V/div.

Top: M_s = 6.41 P_1 = 5.4 mm Hg I_o = 15 ma R_o = 45.3Ω

Bottom: M_s = 6.08 P_1 = 4.6 mm Hg I_o = 15 ma R_o = 45.3Ω

July 1, 1956

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